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Life cycle assessment of the air emissions during building construction process: A case study in Hong Kong

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ABSTRACT

The generation of significant amount of emissions from building construction process has led the promotion of controlling emissions as an important strategy for implementing sustainable development principles in the built environment. The emissions incurred during various stages include carbon dioxide, methane, nitrous oxide, sulphur dioxide, carbon monoxide, nitrogen oxide, non methane volatile organic compounds and particulate matter. This paper conducts the life cycle assessment of the air emissions by using a particular case to examine emissions during construction stage. This study examines the emissions sources in each of the six stages and presents an inventory analysis method to measure air emissions to quantify the air emissions during the six life cycle stages for buildings. This method can help evaluating the impacts of implementing a building on the air quality, thus actions can be taken in early stages to reduce the environmental impacts during building life cycle. A case study is presented to demonstrate the practical application of the method with reference to the building practices for all life cycle stages in Hong Kong.

Contents

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1. Introduction

Improvement of environmental performance of buildings has become an important issue in high densely populated cities, such as Hong Kong. It is well known that, of several sources causing environmental pollution, air emissions from the buildings is one of the major contributing compounds [1]. This has raised the questions what are the major types of air emissions and how the air emissions should be measured for buildings. Air emission, defined as the substances emitted into the atmosphere by human and natural activities which can cause many current and potential environmental problems, including acidification and eutrophication, air quality degradation, global warming/climate change, damage and soiling of buildings and other structures, stratospheric ozone depletion, human and ecosystem exposure to hazardous substances [2]. There are many types of sources of air emissions and many examples (often millions) for each type, such as power plants, factories, domestic households, buildings, cars and other vehicles.

Building construction sector is the second largest carbon dioxide (CO_2) emitter, representing approximately 33% of the global total quantity [3]. In this context, it is significant to mitigate emissions in construction in order to improve the environment quality and finally contribute to the mission of sustainable development. There are various methodologies developed for assessing building environment performance. For example, life cycle assessment (LCA) established a strategic role for evaluating both energy and environmental performances [4]. Vince et al. proposed that LCA can provide an adequate instrument for environmental decision support [5]. Input/output research approach, introduced by Lave et al. [6], is based on input/output tables, where the inputs include energy and natural resources, and the outputs may include CO_2 and other gases emissions. The state of California in U.S.A. has pioneered the introduction of a CO_2 performance standard approach to reduce CO_2 emissions from coal plant, followed by several other states [7]. The responsibility of reducing CO_2 emissions has also been loaded on construction industry. For example, by using building life cycle CO_2 emission database in the context of Taiwan, Zhang investigated the way of reducing a building's environmental burden by establishing a forecast formula to calculate CO_2 emission index [8]. The environmental performance evaluation has aroused strong interests to many countries and many disciplines, such as the manufacturing industry [9,10] and construction industry, leading to the development of various environmental performance assessment systems such as the Building Research Establishment's Environmental Assessment Method (BREEAM) from United Kingdom [11], Leadership in Energy and Environmental Design (LEED) from United States [12], Green Star from Australia [13], and the Hong Kong Building Environmental Assessment Method (HKBEAM) from Hong Kong [14]. In particular, the GBTool is considered as the most comprehensive framework, which has been applied in the international context for over 20 countries [15]. In recent years, several new building environmental assessment tools have been introduced, such as the Japanese Comprehensive Assessment Scheme for Building Environmental Efficiency (CASBEE) [16]; the South African Sustainable Building Assessment Tool (SBAT) [17]; Arup's Sustainable Project Appraisal Routine (SPeAR®) [18]; and the Hong Kong Comprehensive Environmental Performance Assessment Scheme (CEPAS) [19]. These systems have demonstrated new features that differentiate them from the traditional environment assessment approaches, such as the BREEAM.

Though these methods employ scoring methods to assess buildings' environmental performance and the extent to which buildings can contribute to support sustainable patterns of living, they do not offer methods for examining how construction activities generate air emissions which contribute mostly to the pollution of environmental performance. It is considered important to find an alternative approach to address the air emissions in construction activities, thus measures can be taken to mitigate the emissions. Inventory analysis is adopted as the major research method in this study. Inventory analysis has an advantage of examining the air emission not only from a life cycle perspective but also on each of the construction stages by employing calculation models.

In line with the previous literatures, major emissions incurred during building life cycle are classified as carbon dioxide, methane, nitrous oxide, sulphur dioxide, carbon monoxide, nitrogen oxide, non methane volatile organic compounds and particulate matter.

This paper builds on [20] and intends to conduct an inventory analysis in the building construction activities. The main goal of this study is to perform a comprehensive case study to apply the previous calculation model in which the procedures and modelling results that air emissions occurring can be quantitatively assessed with focusing on the building construction activities. The data collected from the case study is quantified in the inventory analysis of the buildings, which provide valuable references to achieve low air emissions goal for other similar building construction activities. By applying the case study, it can show the accuracy of the developed model and its limitation as well for further improvement.

2. Understanding the life cycle assessment (LCA) on air emissions

Life Cycle Assessment is based on the concept of Life Cycle Thinking which integrates consumption and production strategies over a whole life cycle. ISO 14040 [21] defines LCA as:

"... a technique for assessing the environmental aspects and potential impacts associated with a product, by

- compiling an inventory of relevant inputs and outputs of a product system;
- evaluating the potential environmental impacts associated with those inputs and outputs;
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study."

While buildings are responsible for a major portion of the overall energy use, they also account for a major share of material and energy consumption and for the generation of environmental emissions, both nationally and globally [22]. Life cycle assessment has therefore been widely applied in the building sectors of the construction industry. One of the major areas to use life cycle assessment methods is to evaluate and promote the sustainable construction in general, in addition to the green certification of buildings [23,24]. Besides, Forsberg and Malmborg value LCA as a quantitative approach for making construction decisions [25]. The following sections will address the three major areas of literatures.

2.1. LCA applications for construction industry

LCA has been used in the building sector since 1990 and is an important tool for assessing buildings (Taborianski and Prado [26], Fava [27]). In a brief analysis on the evaluation of environmental impact of the building life cycle, Peuportier compared

three types of houses with different specifications located in France [28]. According to the applied LCA research into a new university building by Scheuer et al. [20], almost 60 building materials were identified for the inventory analysis. The results showed that in the positioning of materials phase, the total embodied primary energy was 51×106 MJ over the building life cycle. Huijbregts et al. expressed concern regarding various uncertainties related with LCA and presented a methodology to quantify parameters, scenario, and model uncertainty simultaneously, using a residential-insulation case study [30]. The main aim of the study by Adalberth et al. [31] is to evaluate the life cycle of four dwellings located in Sweden with different construction characteristics. Considering an occupation phase of 50 years for the dwellings, this study concluded that the greatest environmental impact occurs during the use phase. Approximately 85% and 15% of energy consumption occurs during the occupation and manufacturing phases, respectively.

Overall, it can be indicated from these literatures that the evaluation of environmental impact of the building life cycle are mostly focused by using LCA method in the application for construction industry.

2.2. LCA application in the construction stage

Life Cycle Assessment (LCA) methodology is widely adopted to evaluate the environmental loads of processes and products during their whole life-cycle. In line with the findings from the existing literatures from a whole building life cycle perspective, the phase with the highest environmental impact is the operation stage with approximately 80–90% of the overall life cycles', while the constructions stage accounted for a total of 8–20% [28,30–32]. One of the comprehensive analyses on the environmental impact of the construction phase was performed by Asif et al. [33]. And the study concluded that the material used in the house with the highest level of embodied energy was concrete. Following by him, Dimoudi and Tompa evaluated the energy and environmental indicators of an office building at the construction stage in Greece [34]. The results indicate that the external wall is contributing the maximum in the overall embodied energy of the building. Treolar et al. presented an evaluation of the embodied energy content of several commonly used construction materials at the construction stage, using a case study in Australia [35]. The results showed that the building's embodied energy content from the materials as well as from various building elements (e.g., roof, services, etc.). Jian et al. [36] then analysed the LCA of urban project development through the calculation of CO_2 emissions during construction, maintenance and operation of facilities and public buildings, and their environmental impacts.

In summary, the existing published research on LCA for the construction phase is limited and a consensus on methodology or approaches has not fully developed.

2.3. LCA Applications in studying air emissions for buildings

There are various types of air emissions from developing and operating a building. It is important to understand air emissions from a perspective of building life cycle. Asif et al. conducted process-based LCA for materials used in residential construction in Scotland; eight commonly used construction materials from the energy use and air emissions have been assessed during the construction phase [33]. On the other hand, there are various classifications on air emissions. For example, according to Hong Kong Environmental Protection Department, the emission inventory consists of five major air pollutants, namely: sulphur dioxide (SO_2), nitrogen oxides (NO_X), respirable suspended PM (RSP or PM_{10}), volatile organic compounds (VOC) and carbon monoxide (CO) [37]. EPA (US Environment Protection Agency) refers six major air pollutants (also called the criteria pollutants): NO_2, O_3 (ozone), SO_2, PM (particulate matter), CO, and Pb (lead) [38]. There are other classifications, for example, UNFCCC [39], classifying CO_2, CH_4, N_2O, PFC_S (perfluorocarbons), HFC_S (hydrofluorocarbons), SF_6 (sulphur hexafluoride) as direct greenhouse gases, and SO_2, NO_X, CO, NMVOC (non methane volatile organic compounds) as indirect greenhouse gases. The major emissions in a building life cycle include CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM.

According to the previous study, the major air emissions introduced in the building material manufacturing stage are CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC (as well as caused by calcinations, evaporation process, and material surface coating volatilization) and PM. These air emissions are mainly the result of fuel combustion activities and electricity use for operating equipment. The typical air emissions in the building materials transportation stage are CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM (only caused by diesel combustion in this stage) [40]. These emissions are mainly resulted by the fuel combustion activities for operating vehicles during the construction material transportation process. During construction stage, the air emissions CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC (as well as caused by using paint, other surface coating and ordinary solvents) and PM (caused by diesel combustion and electricity use) are present [40]. These emissions are the results from the fuel combustion activities and electricity use for operating mobiles and equipment. During the building operation and maintenance stage, the typical air emissions include CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC (as well as caused by calcinations, evaporation process, and material surface coating volatilization) and PM (caused by diesel combustion and electricity use and construction dust in this stage) [40]. These emissions are generated from utilising the fossil fuels and consuming electricity in daily life (e.g. air-conditioning, lighting, cooking, washing, and electrical equipment). The emissions in the maintenance stage are also produced in the process of materials manufacturing and transportation. The emissions in an indoor environment have also been investigated by Arjen et al. [41]. He studied the total amount of building materials which humans were exposed to in the use phase of a Dutch home. The emission of radon was 59%, the highest contaminant and harmful to human health; 38.7% for gamma radiating elements; 1.3%, 0.8% and 0.2% formaldehyde, toluene and others, respectively.

Furthermore, building demolition and waste disposal will also generate emissions, typically including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM (caused by diesel combustion and electricity use and construction dust in this stage) [40]. They are the results of the fuel combustion activities and electricity use for operating various demolition and waste disposal equipment and facilities.

In applying the LCA methodology for buildings, there are four distinct analytical steps: defining the goal and scope, creating the life-cycle inventory, assessing the impact and finally interpreting the results [42]. Based on these literature reviews, this paper therefore focused on studying the air emissions sources. The emissions sources in each of the six stages are investigated by applying the inventory analysis method, which can be used to quantify the air emissions during the six life cycle stages for buildings. This method can help evaluating the impacts of implementing a building on the air quality, thus actions can be taken in early stages to reduce the environmental impacts during building life cycle. The method is later presented by using a case study with reference to the building practices for all life cycle stages in Hong Kong.

Table 1
Emission factors from the seven major building materials at manufacture stage (g/kg).

Material	Emission factors							
	CO_2 [a]	CH_4	N_2O	SO_2	CO	NO_X	NMVOC	PM
Concrete	106 [a]	ND	ND	0.0039 [b]	0.0081 [b]	0.0045 [b]	0.0042 [b]	0.0016 [b]
Cement	994 [a]	0.0273 [c]	0.0273 [c]	1.3217 [c]	0.6281 [c]	2.4413 [c]	0.0273 [c]	0.6 [d]
Steel	1242 [a]	1.3714 [c]	0.0259 [c]	5.2009 [c]	92.8913 [c]	2.7428 [c]	1.8113 [c]	2.03 [d]
Aluminium	8000 [a]	ND [c]	ND [c]	54.4 [c]	441.6 [c]	6.4 [c]	1.6 [c]	49 [d]
Glass	1735 [a]	ND [c]	ND [c]	10.8719 [c]	0.4626 [c]	16.6549 [c]	0.2313 [c]	0.4 [d]
Sand	6.9 [a]	ND	ND	0.00014 [e]	0.0189 [e]	0.016 [f]	0.00124 [e]	1.1453 [f]
Timber	−1665 [a]	0.00065 [g]	ND	0.01 [g]	0.8 [g]	0.55 [g]	0.475 [g]	0.35 [g]

Note: ND means no data.

[a] Ref. [45].
[b] Ref. [46].
[c] Based on the emission factor of CO_2, calculated by the portion of emission of CO_2, CH_4, N_2O, SO_2, CO, NO_X and NMVOC in production of cement, steel, aluminium and glass, respectively, due to the emission data of Europe 28 countries [1].
[d] Ref. [47].
[e] Ref. [48].
[f] Ref. [49].
[g] Ref. [50].

3. Research methods

Two major research methods are employed in this study: (1) inventory analysis approach; and (2) case study. The inventory analysis generally uses databases of building materials and component combinations [43]. There are three steps to conduct the inventory analysis for quantifying air emissions:

- the identification of inventory analysis components (refer to Section 2);
- the calculation procedures for air emissions; and
- the presentation of inventory analysis results.

Case studies can also be used for explorative, descriptive, explanatory or illustrative research [44]. In this study, a comprehensive case study is employed as the exemplar building to demonstrate how the air emissions can be quantified by using the following model:

$$Emissions = AD \times EF \tag{1}$$

where *AD* denotes activity volume; and *EF* is emission coefficient representing the emissions volume per unit activity.

By applying the formula (1) to a building's life cycle including: building materials manufacture stage, building materials transportation stage, construction stage, operation and maintenance stage, demolition stage, and construction waste disposal stage, the calculation on emissions will be produced. The calculation procedures for emissions in different building life cycle stages will be elaborated in the following section.

4. Calculation procedures for air emissions

In order to implement the inventory analysis on the air emissions, the calculation procedure is the second step to achieve the goal. According to the principles in the model (1), the emissions in individual building stages can be expressed as follows:

The emissions in the process of manufacturing building materials

$$Emissions_{1i} = \sum Q_j \times EF_{ij} \tag{2}$$

where i (i=1, ..., 8) denotes a type of emissions, including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM generated by the production of each material; j (j=1, ..., 7) denotes one of the materials, including concrete, cement, steel, aluminium, glass, sand and timber; $Emissions_{1i}$ is the amount of emission i in materials manufacture stage, wherein, "1" denotes the material manufacture stage; Q_j denotes the quantity of material j (kg); and EF_{ij} is the emission factor of the emission i generated by producing a unit of material j (g/kg).

It is important to get the values of emission factors. By referring to various standards, the emission factors from seven major building materials at manufacture stage are shown in Table 1.

4.1. The emissions in the process of transporting building materials

Transportation for building materials can be arranged through road transport, railway transport, aviation transport, and sea transport. The emissions can be calculated by

$$Emissions_{2i} = \sum Q_j \times D_{jr} \times EF_{ir} \tag{3}$$

where i (i=1,..., 8) denotes one of the emissions, including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM; j (j=1,..., 7) denotes one of the materials, including concrete, cement, steel, aluminium, glass, sand and timber; $Emissions_{2i}$ is the amount of emission i in the transportation stage (g); r (r=1,..., 4) denotes the transportation method of building materials, including deep-sea transport, coastal vessel, road freight and railroad; Q_j denotes the quantity of building material j (ton); D_{jr} is the total distance of transportation for building materials j by transportation method r (km); and EF_{ir} is the emission factor of emission i by transportation method r (g/ton km).

Table 3 shows the emission factors for the transportation of building materials by several transportation methods, wherein, Emission factor (g/ton km)=Energy use (MJ/ton km) × Fuel emission factor (g/MJ) (Energy use and fuel emission factor are shown in Table 2).

4.2. Emissions in building construction stage

In the construction stage, emissions are mainly generated from temporary electric power use, the fuel combustion of construction equipments and from the transportation of construction waste

$$Emissions_{3i} = \sum Q_j \times EF_{ij} + \sum Q_r \times D_r \times EF_i \tag{4}$$

where i (i=1, ..., 8) denotes one of the emissions, including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM; j (j=1, 2) denotes one of energy, including diesel and the electricity; $Emissions_{3i}$ is the amount of emission i at construction stage (g); Q_j denotes the

Table 2
Emission factors for transportation of building materials.

Transportation method	Energy use (MJ/ton km)[a]	Fuel type	Fuel emission factor (g/MJ)[b]							
			CO_2	CH_4	N_2O	SO_2	CO	NO_X	NMVOC	PM[c]
Deep-sea transport	0.216	Heavy fuel oil	74	0.0017	0.0047	0.468	0.1733	1.335	0.0545	81.0
Coastal vessel	0.468	Heavy fuel oil	74	0.0017	0.0047	0.468	0.1733	1.335	0.0545	81.0
Road Freight	2.275	Diesel	74	0.0057	0.0028	0.002	0.1194	0.493	0.0619	63.1
Railroad	0.275	Diesel	74	0.0084	0.002	0.002	0.1035	0.691	0.0432	77.6

[a] Ref. [51].
[b] Ref. [52].
[c] Ref. [53].

Table 3
Emission factors for building materials at transportation stage.

Transportation method	Emission factor (g/ton km)							
	CO_2	CH_4	N_2O	SO_2	CO	NO_X	NMVOC	PM
Deep-sea transport	15.98	0.0004	0.0010	0.1011	0.0374	0.2884	0.0118	17.50
Coastal vessel	34.63	0.0008	0.0022	0.2190	0.0811	0.6247	0.0255	37.91
Road Freight	168.35	0.0130	0.0064	0.0046	0.2716	1.1216	0.1408	143.55
Railroad	20.35	0.0023	0.0006	0.0006	0.0285	0.1900	0.0119	21.34

Table 4
Emission factors for diesel and electricity consumption.

Energy	Emission factor							
	CO_2	CH_4	N_2O	SO_2	CO	NO_X	NMVOC	PM
Diesel (g/L)[a]	2930.40	0.06	0.0792	9.27	0.48	11.88	0.06	12.96[b]
Electricity (g/kWh)	700.00[c]	0.01[d]	0.09[d]	2.00[e]	0.51[f]	1.00[e]	0.44[g]	0.10[e]

[a] Ref. [52], wherein, 1 l=39.6 MJ (http://esvc000266.wic046u.server-web.com/ecflist.html).
[b] Ref. [54].
[c] Ref. [55].
[d] Ref. [56], wherein, 0.0192 lbs/MWH=0.0872 g/kWh.
[e] Ref. [57].
[f] Ref. [58].
[g] Ref. [59], wherein, 0.000705 lb/hp hr=0.4352 g/kWh.

quantity of energy j use (liter or kWh); EF_{ij} denotes the emission factor of emission i generated by energy j consumption (g/liter or g/kWh) (the values of the emission factors for diesel and electricity are shown in Table 5); Q_r denotes the quantity of waste transported to landfill r (ton); D_r denotes the distance between construction site and landfill r (km); and EF_i denotes the emission factor of emission i due to waste transportation (g/ton, km) (the value of emission factor is shown in Tables 3 and 4).

4.3. Emissions in the operation and maintenance stage

Emissions from the operation stage are largely from using combustion devices for operating buildings, which boilers, burners, turbines, heaters, furnaces, ovens, dryers, internal combustion engines (e.g. emergency electricity generator), lift, and any other equipment or machinery. The amount of operation emission can be calculated by the following equation:

$$Emissions'_{4i} = \sum Q_j \times EF_{ij} \times years \quad (5)$$

where i (i=1, …, 8) denotes one of emissions, including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM; j (j=1, …, 3) denotes one of energy including town gas, diesel and electricity; $Emissions'_{4i}$ is the amount of emission i generated from the fuel combusted or electricity use (g); Q_j denotes the quantity of energy j use (liter/per or kWh/per); and EF_{ij} denotes the emission factor i generated by energy j use (g/liter or g/kWh) (The emission factors for diesel and electricity are shown in Table 5, and the emission factors for town gas are shown in Table 5).

Table 5
Emission factors from town gas (Source: Ürge-Vorsatz and Novikova [3]).

Energy	Emissions (g/MJ)							
	CO_2	CH_4	N_2O	SO_2	CO	NO_X	NMVOC	PM
Town gas	55.5	0.001	0.002	0.001	0.010	0.17	0.005	0.001[a]

[a] Ref. [60].

On the other hand, the emissions from maintenance works are suggested as 0.2% of the total amount of air emissions in construction stage [8].

4.4. Air emissions in demolition stage

Emissions will be generated during building demolition process, which can be calculated by the following equation:

$$Emissions_{5i} = \sum Q_j \times EF_{ij} \quad (6)$$

where i (i=1, …, 8) denotes one of emissions, including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM; $Emissions_{5i}$ is the amount of

emission i generated by energy use in demolition stage (g); Q_j denotes the quantity of energy j consumed by equipments, including diesel and electricity (liter or kWh); and EF_{ij} denotes emission factor of emission i generated by energy j (g/liter or g/kWh) (shown in Table 5).

4.5. Air emissions in the construction waste disposal stage

The emissions in construction waste disposal stage are largely generated by the transportation of demolition wastes, which can be calculated by the following equation:

$$Emissions_{6i} = \sum Q_r \times D_r \times EF_i \quad (7)$$

where i (i=1, …, 8) denotes one of emissions, including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM; $Emissions_{6i}$ is the amount of emission i during the disposal stage (g); Q_r denotes the quantity of waste transported to landfill r (ton); D_r denotes the distance between construction site and landfill r (km); and EF_i denotes the emission factor of emission i due to waste transportation (g/ton km) (shown in Table 3, Railroad emission factor).

5. Case study on the application of emission calculation model

The practical case chosen for demonstrating the application of emission calculation model, called One Peking, is a thirty-story high commercial building in Hong Kong, with CFA of 43,210 m^2. It was built during the period from August 2001 to April 2003, with typical raft foundation and reinforced concrete structure frame. The building was awarded the 'Excellent' rate by HKBEAM. The lifespan of the building is assumed to be 50 years.

5.1. Data for analysis

The data used for analysis are from the report by the Electrical and Mechanical Service Department of Hong Kong [63] and the publication by Yan et al. [63]. These data are summarised in Tables 6–8. These data are applied in this study to demonstrate the effectiveness of the application of the calculation procedures introduced in this study for emissions. By referring to these data, calculations on the emissions in different building life cycle stages for the concerned One Peaking project can be conducted.

Table 6
Major building materials of One Peking.
(*Source*: EMSD [61,63]).

Material	Country of origin	Distance from site (km)		Quantity (ton)
		Land	Sea	
Concrete	HK	30.0[a]	0.0[b]	59,628.0
Concrete	China	250.0	150.0	1445.9
Cement	China	250.0	150.0	2.7
Steel	China	250.0	150.0	6125.6
Glass	China	250.0	150.0	190.3
Sand	China	250.0	150.0	19,674.1
Timber	China	250.0	150.0	96.2
Aluminium	China	250.0	150.0	65.7
Aluminium	UK	877.9	18,240.0	0.6
Aluminium	USA	5463.4	18,753.3	0.4
Glass	Singapore	4511.1	2496.7	0.2
Total	–	–	–	87,229.7

[a] This is a assumed average distance.
[b] Ref. [62].

Table 7
Fuel consumption and solid waste generated during construction stage of One Peking [63].

Item	Quantity	Unit
Electricity	1,590,680	kWh
Diesel	246,001	Liter
Waste	33,792	Ton

Table 8
Annual energy consumption of One Peking.

Energy type	Consumption value	Unit
Town gas	63,243,020	MJ
Diesel oil	648,737[a]	Liter
Electricity	35,258,333[b]	kWh

[a] Refs. [19,20], wherein, 1 l=39.6 MJ (http://esvc000266.wic046u.server-web.com/ecflist.html).
[b] 1 kWh=3.6 MJ.

It can be seen that the main building materials used in the case study project include concrete, cement, steel, glass, sand, timber, and aluminium. The transportation of materials has the average distance of 30 km.

Table 8 shows the data about the fuel consumption and solid waste generated during construction stage in the case study project. The waste disposal distance between the project site and landfill is 20 km.

The data about the energy consumption during the operation and maintenance stage of the case study project is not available. As an alternative approach, the average value of energy use per commercial building area per year of the whole Hong Kong is applied to the case study. According to the energy end use data of Hong Kong [63] and the Hong Kong annual digest of statistics [64], the commercial sector in Hong Kong in 2006 consumed a total of 1463.62 MJ/m^2 town gas, 594.63 MJ/m^2 diesel oil and 11269.03 MJ/m^2 electricity. Assuming the building operation period as 50 years, the calculation of the annual energy consumption is therefore presented in Table 8, applied to the case study project.

The data about the energy consumption in demolition stage is not available as the building is still in use. Thus it is needed to estimate the air emission data in the demolition stage. According to Ürge-Vorsatz and Novikova [3], a building usually consumed 0.8 l diesel oil per m^2 in the demolition stage, the total demolition work of the case study project can therefore consume 34,568 l diesel oil.

Considering the construction waste disposal, aaccording to reference [63], the total weight of materials of the project concerned is 87264.8 t, composing of concrete, cement, steel, glass, sand, timber, and aluminium, as shown in Table 7.

5.2. Results

By using formulas (1)–(7) and the data presented in Section 5.1, we can calculate the value of the emissions of CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM from each of the life cycle stage for the case study project, and the results are shown in Table 9.

It can be seen from Table 9 that the CO_2, N_2O, SO_2, NO_X and NMVOC emissions occupy only a small proportion which is less than 2% at the building materials manufacture stage. Whilst in this stage, the CH_4 and CO emissions account for 33.81% and 38.72% respectively.

In the building materials transportation stage, PM emissions account for 35.58%, while other types of emissions only

Table 9
Amount and proportion of air emissions during the life cycle of One Peking Project.

Stage of building life cycle	CO_2		CH_4		N_2O		SO_2		CO		NO_X		NMVOC		PM	
	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%	Amount (kg)	%
Building materials manufacture	1,492,4208.19	0.98	8400.78	33.81	158.73	0.10	37,803.68	0.98	599,502.99	38.72	21,050.05	0.77	11572.76	1.45	38445.22	1.83
Building materials transportation	839,078.38	0.06	57.54	0.23	35.31	0.02	897.95	0.02	1454.69	0.09	7171.70	0.26	688.16	0.09	74,9147.41	35.58
Construction	194,8134.99	0.14	32.94	0.17	162.52	0.10	5464.01	0.14	1111.70	0.08	5271.19	0.22	802.03	0.11	10,0364.07	9.37
Operation and maintenance	1,504,788,794.24	98.78	16,302.12	65.60	163,900.74	99.77	3,827,110.64	98.85	944,969.30	61.04	2,686,359.22	98.58	78,5039.03	98.29	609,239.37	29.40
Demolition	101,298.07	0.01	2.05	0.01	2.74	0.00	320.32	0.01	16.43	0.00	410.67	0.02	2.05	0.00	448.00	0.02
Construction waste disposal	293,820.58	0.04	22.69	0.18	11.17	0.01	8.03	0.00	474.02	0.06	1957.52	0.14	245.74	0.06	250,537.24	23.80
Total	152,2895,334.45	100	24,818.12	100	164,271.21	100	3,871,604.63	100	1,547,529.13	100	2,722,220.35	100	798,349.77	100	1,748,181.31	100

contribute less than 0.3% at this stage. This indicates that the transportation of building materials do not generate much air emissions. Similarly, in the construction stage, the proportions of the CO_2, N_2O, SO_2, CO, NO_X and NMVOC emissions is less than 0.25% of the total amount of emissions. PM emission nevertheless contributes the major part with 9.37%, which has a large influence on the air pollution in the construction process.

In examining the operation and maintenance stage, it is interesting to note that CO_2, N_2O, SO_2, NO_X and NMVOC emissions account for 98% of the total emissions in this stage. PM emission accounts for 29.40%.Operation and maintenance stage contributes to major proportions of all types of emissions in the building life cycle.

In the demolition and construction waste disposal stage, less than 0.03% of CO_2, N_2O, SO_2, CO, NO_X and NMVOC emissions are generated, and the proportion of PM emission is 0.02%. However, the proportion of PM emission becomes 23.80% in the construction waste disposal stage.

There are three typical types of air emissions worth for further discussion. Seen from Fig. 1, CH_4, CO and PM emissions have different proportion at different life cycle stage of the buildings. As for CH4 and CO, the largest amount is produced in the operation and maintenance stage, while the second largest amount is produced from the building material manufacture stage. The PM emission spread at different life cycle stages of buildings, including 34.85% at the operation and maintenance stage, 42.85% at the building materials transportation stage, 14.33% at construction waste disposal stage, and 7.97% at the demolition stage.

The result indicates that, in the whole life cycle stages of buildings, operation and maintenance of stages contribute the most of air emissions in building construction. The major emissions include the CO_2, CH_4, N_2O, SO_2, CO, NO_X and NMVOC. Furthermore, different amount of air emissions and different types of them are produced at different life cycle stages of buildings.

By arranging different types of building materials and using different energy-saving construction measures at different life cycle stages, we can make lower air emissions in building construction. In particular, more emphasise should be given to the measures for reducing the air emissions at the operation and maintenance stage.

6. Conclusions

Air emissions are generated during building life cycle which typically include building materials manufacture stage, building materials transportation stage, construction stage, operation and maintenance stage, demolition stage, and construction waste disposal stage. In this paper, eight types of air emissions during building life cycle including CO_2, CH_4, N_2O, SO_2, CO, NO_X, NMVOC and PM were analysed through a constructive case study. Calculation procedures for assessing these emissions were presented, by which these air emissions in this specific project called One Peaking were quantified. It demonstrates that air emissions during building life cycle can be measured quantitatively. This provides important mechanism to understand the impact of buildings on the environmental performance. By referring to the case study, One Peking, we found that over 98% of CO_2, N_2O, SO_2, NO_X and NMVOC emissions are from the operation and maintenance stage, whilst the CO_2, N_2O, SO_2, NO_X and NMVOC emissions occupy only a small proportion which is less than 2% at the other stages during building life cycle.

By quantifying the air emissions at each of building life cycle stages of buildings, it is therefore feasible to predict the quantity

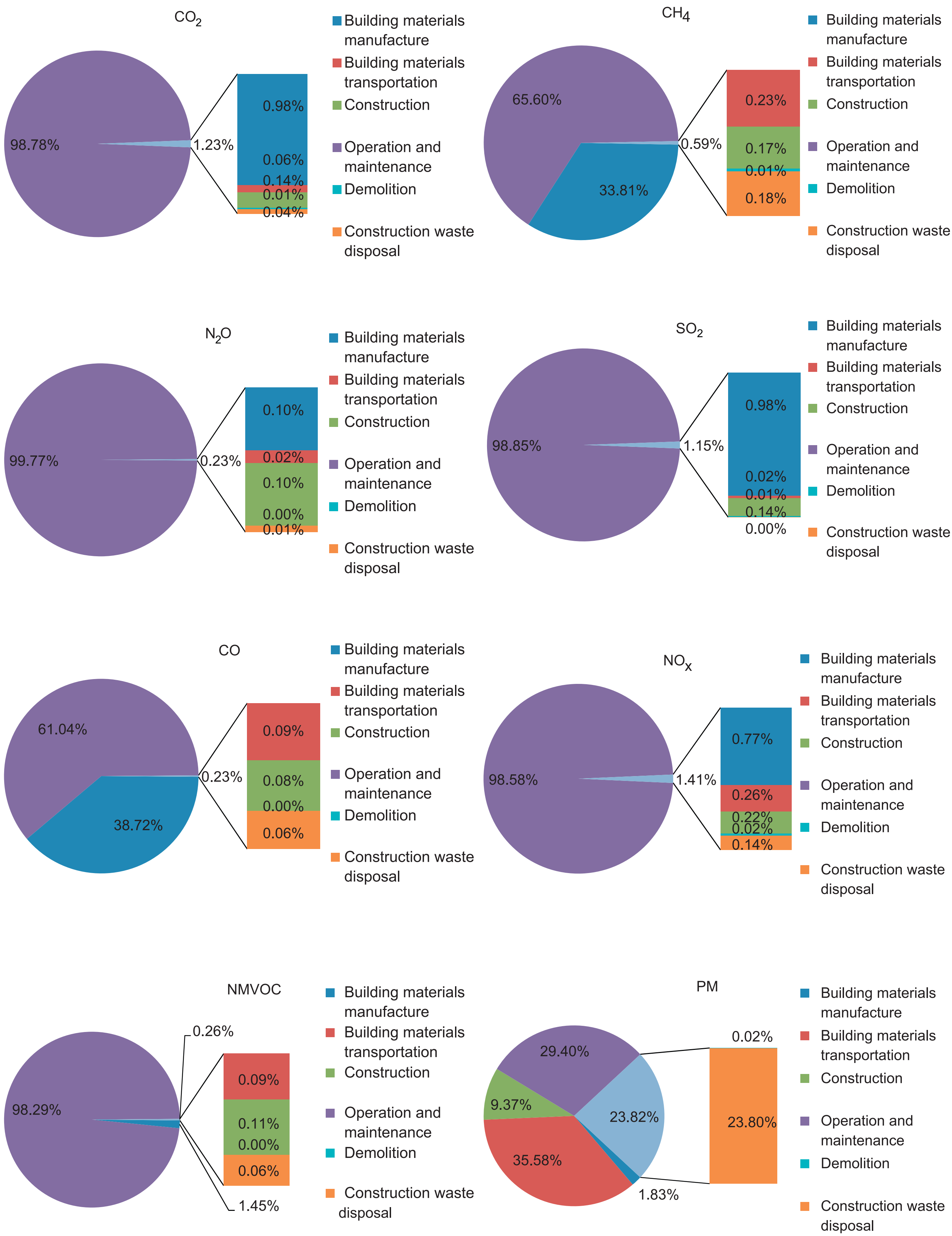

Fig. 1. Proportion of air emissions in different stages during the life cycle stages of One Peaking Project.

of air emissions. This quantitative approach allows for analysing the emission quantity from developing buildings when different types of building materials and construction methods are used. The analysis results can help identify the optimal solution in choosing building materials, construction methods and the ways of using the buildings towards minimising the quantity of air emissions. In this way, the environmental performance in terms of air quality can be improved as the air emissions are reduced in the building arena. This way therefore also contributes to the mission of sustainable development

The case project referred in this study is with reinforced concrete structure. However, the methodology presented in this study can be applied to analysing the emissions during the development of other types of buildings. Although it was a local case, the calculation procedures are applicable for understanding life cycle emissions of building in other areas, which could lead to comparative studies on building air emissions in different places.

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